Adaptive Hierarchical Network Modeling and Simulation

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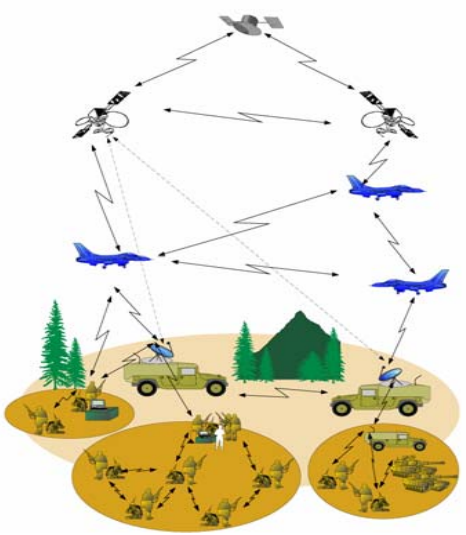
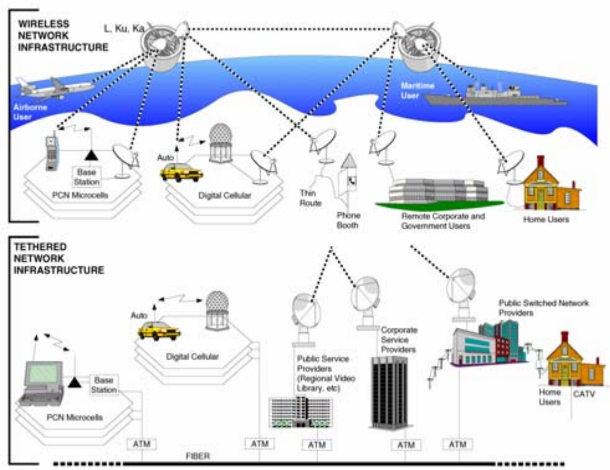
Adaptive Hierarchical Network Modeling and Simulation





NEW IDEAS/METHODS

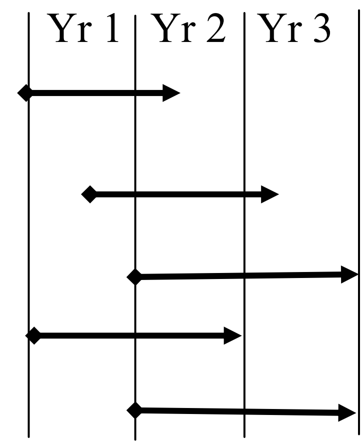
- Robust multi-scale traffic models and model complexity *vs* performance tradeoff
- Hierarchical loss network models and progressive estimates and control
- Self-configurable adaptive hierarchical traffic models linked to network management and control functions

IMPACT

- New network laws for new traffic types (fractal)
- Two to three orders of magnitude faster performance evaluation of large networks
- Enabler of intelligent network management via models
- Accurate network planning and dimensioning

SCHEDULE

Self-similar traffic models and wavelets
Multi-fractal traffic models and wavelets
Queuing theory/control
Aggregation hierarchies
Network design and control on hierarchies



University of Maryland College Park: J.S. Baras, A. Makowski, P. Narayan

Main Goal

- Realize the vision of hierarchical network models that can automatically adapt to traffic characteristics and network management needs

- Focus on new fundamental methods utilizing polymorphic models for traffic, analytical approximations, and hybrid multi-criteria optimization

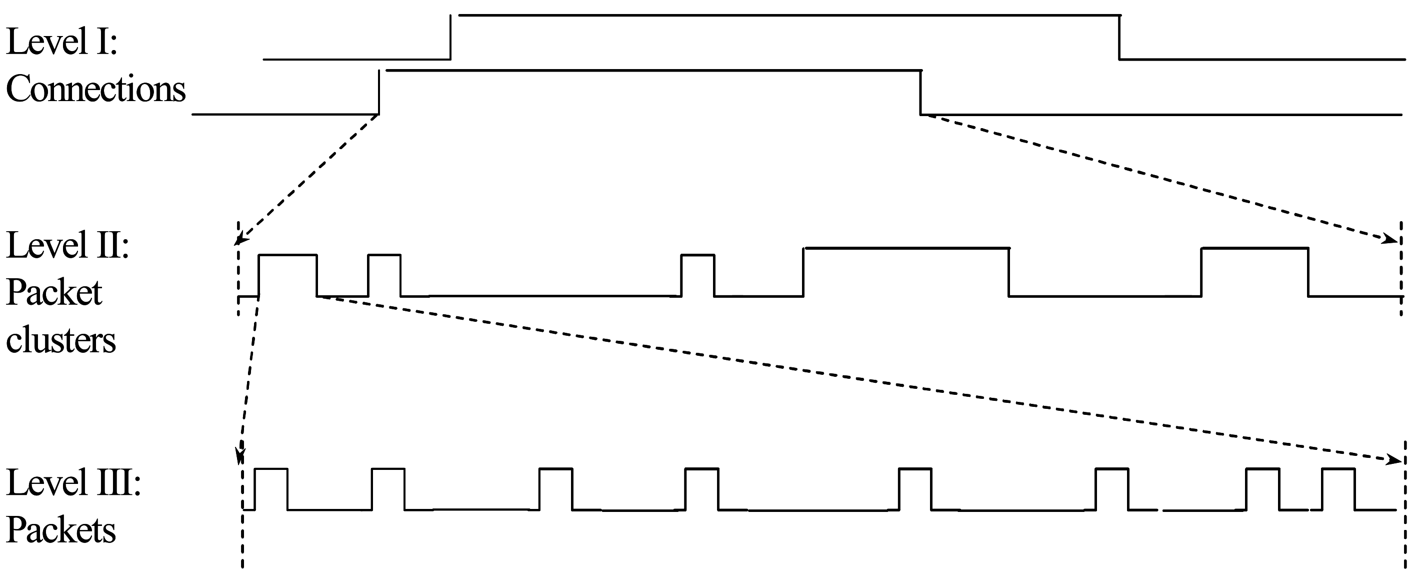
Thrusts

- Network Traffic Models for Control and Planning
- Adaptive Hierarchical Modeling Incorporating On-Line Measurements
- Simulation Experimentation and Validation

Hierarchical On-Off (HOO) Model

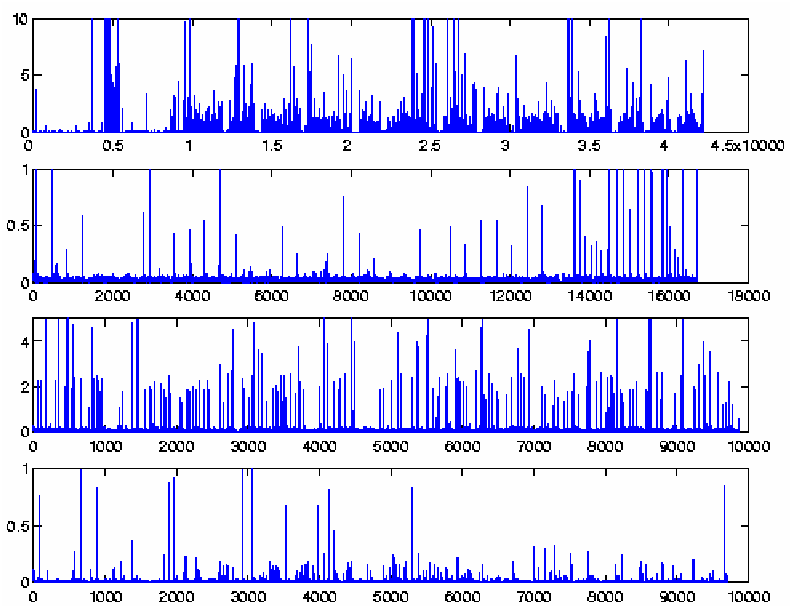
(J.S. Baras, N. Liu, J-S. Jou)

- Structurally imitating TCP traffic in multiple resolutions.
- Involving parameters from connection level to packet level
- Explicitly modeling protocol effect of TCP
- Level I is a G/G/∞ or M/G/∞ process
- Exhibiting long-range dependent and multifractal behaviors

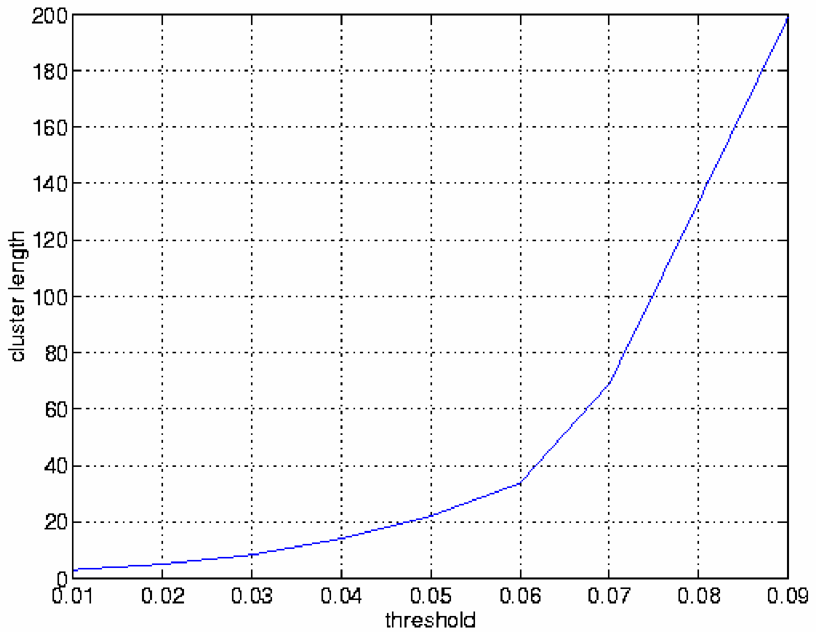


Existence of the Packet Cluster

- Protocol analysis: TCP window-based bulk transfer
  - Regular cluster pattern when there is no packet loss
  - Irregular cluster pattern when there are packet losses
- Physical evidences from traffic data

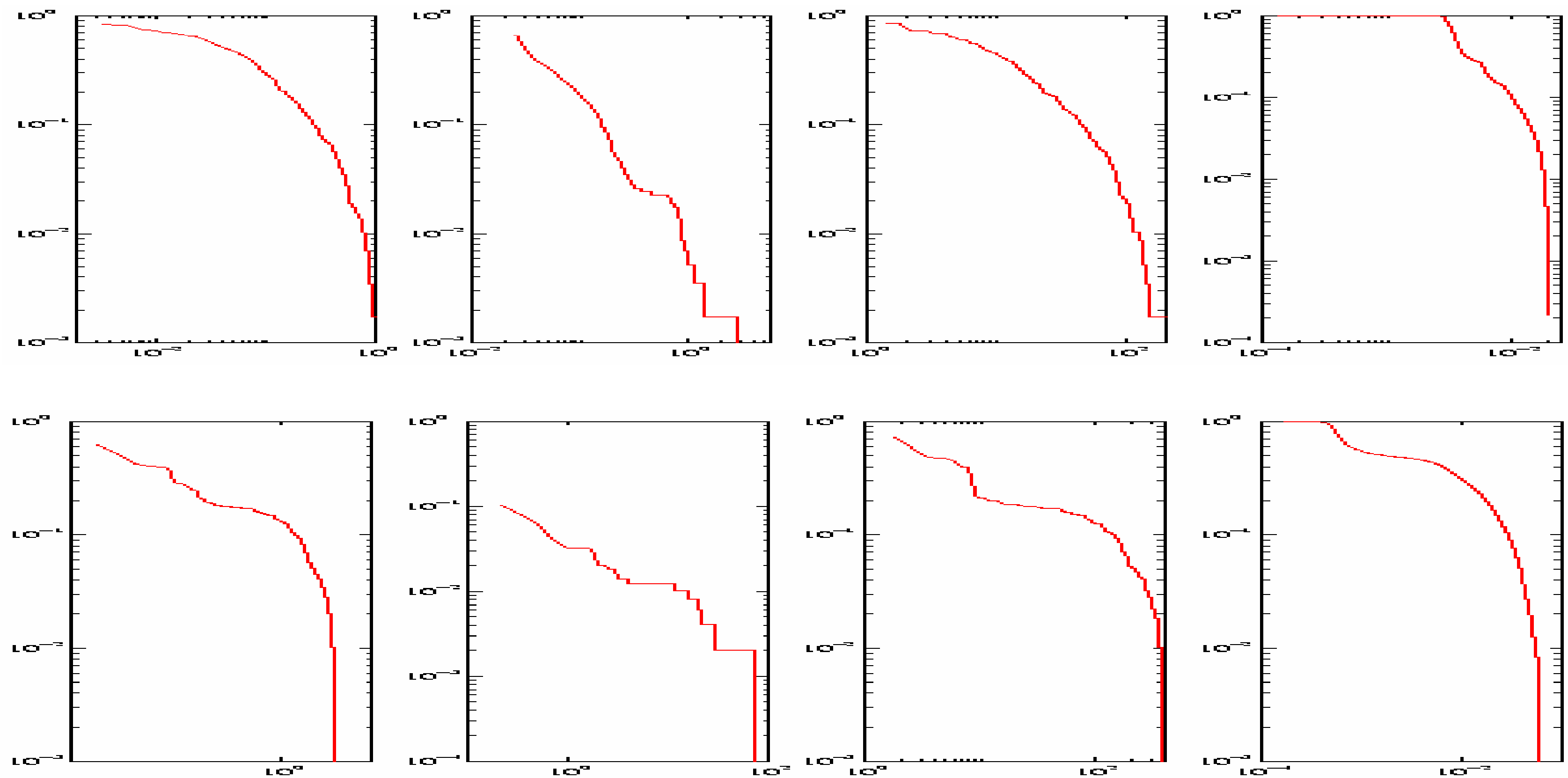


Inter-packet intervals (Top-down: four connections)



Cluster size jump at threshold RTT

Existence of the Packet Cluster (cont.)



From left to right in each row: distributions of the cluster, the inter-cluster interval, the number of packets within a cluster, and the inter-packet interval within a cluster. Row 1 and row 2 are for two connections.

MLE for HOO Parameters

- Heavy-tailed parameters
  - Pareto distribution with two parameters (α, b): $F(x) = 1 - (b/x)^{\alpha}$
  - MLE (Hill estimator):

$$\hat{\alpha} = \frac{k}{\sum_{i=1}^{k} \log \frac{x_i}{x_{k+1}}}$$

$$\hat{\theta} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

$$\hat{b} = \hat{\theta}\hat{\alpha} \big/ (\hat{\alpha} - 1)$$

- Short-tailed parameters
  - Exponential distribution with one parameters θ: $f(x) = \theta e^{-\theta x}$
  - MLE:

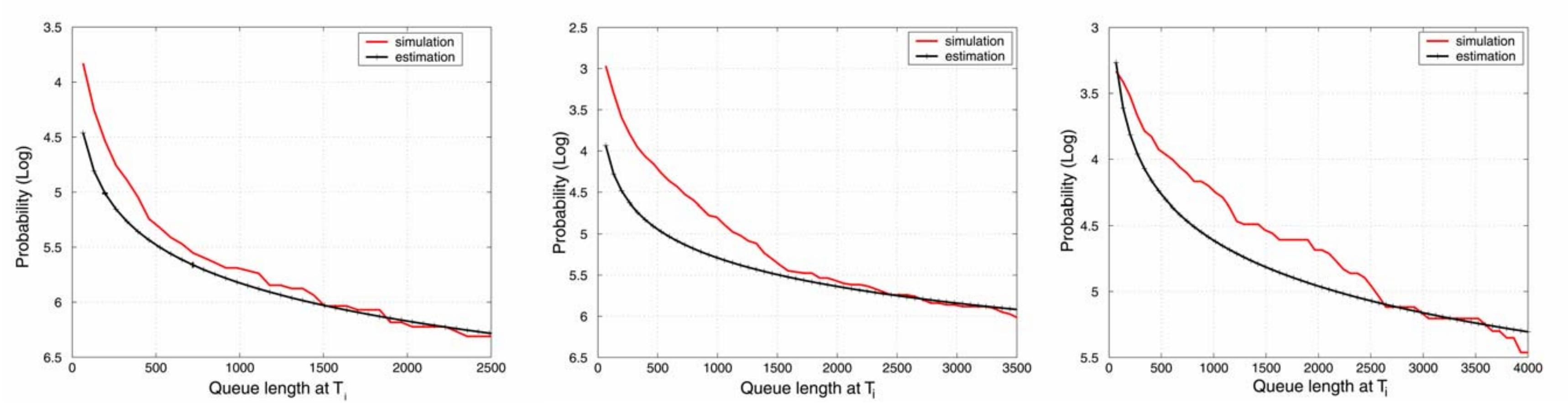
$$\hat{\theta} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

Queueing Analysis of HOO model

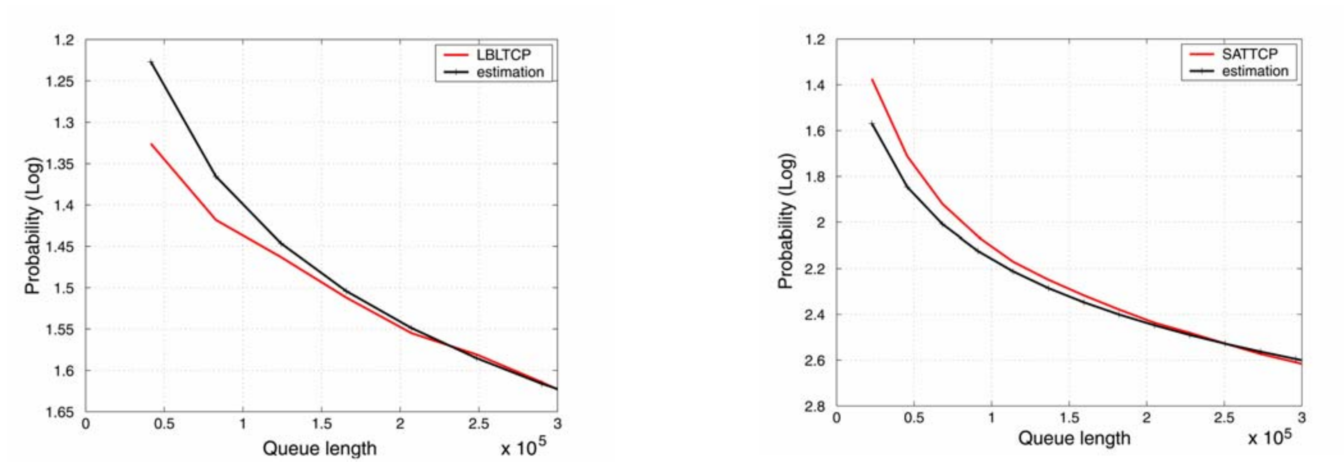
***Theorem*:** For an infinite FIFO queue fed with a HOO process, if the distribution of τ is $F \in P$ with parameters b and α, $\lambda\mu < 1$, $0 < \gamma_1 < 1$, and $0 < \gamma_2 < 1$, then in either case:
1) $r_{on}\gamma_{1,min}\gamma_{2,min} \geq c$, or
2) $r_{on}\gamma_{1,min}\gamma_{2,min} < c$ and $\lambda\mu\, r_{on}\gamma_1\gamma_2 \rightarrow c$, the queue content process at T_i has the following tail

$$P[Q_s > x] \sim \frac{\lambda}{\alpha - 1} \frac{b^{\alpha}(\lambda\mu r_{on}\gamma_1\gamma_2 + r_{on}\gamma_1\gamma_2 - c)^{\alpha}}{c - \lambda\mu r_{on}\gamma_1\gamma_2} x^{-(\alpha-1)},$$

Queueing Analysis of HOO model (cont.)



Comparisons of queue analysis with simulation results for load 20%, 30%, and 80%



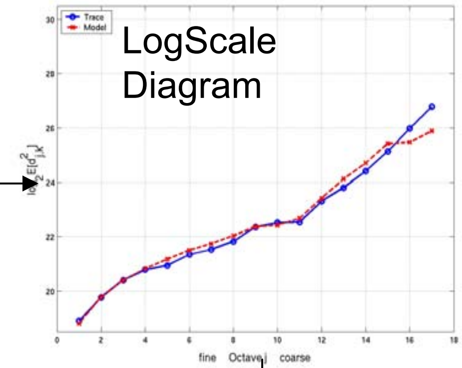
Prediction of queueing performance of real real traces

Multi-Level ON/OFF Model for Multifractal Internet Traffic: Overview

(J.S. Baras, J-S. Jou)

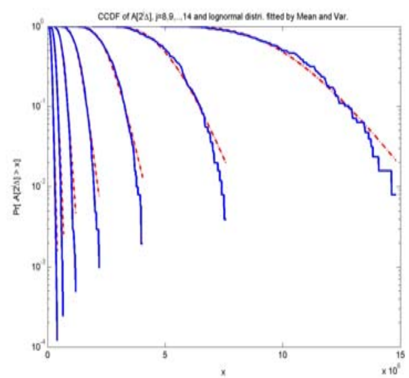
Real Trace → Estimate Parameters → Multilevel ON/OFF Model → Analytical Solution → LogScale Diagram

LogScale Diagram

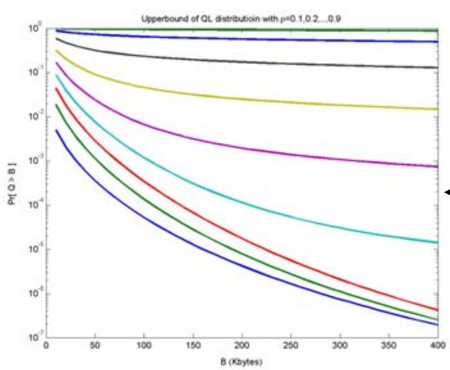


Workload $A[2^j]$ ↓

E $A[2^j]$ & Var($A[2^j]$) → Lognormal Distribution



UpperBound of QL Distri.

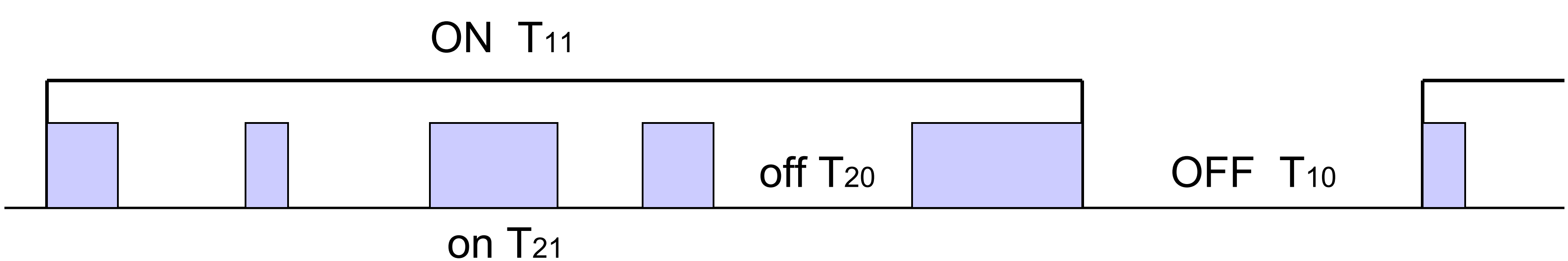


Multilevel ON/OFF model

- T_{11}: TCP session lifetime
- T_{10}: Think time
- T_{21}: Active period (burst)
- T_{20}: Inactive period
- B: Packet rate in active time constant
- RTT:~ $T_{21} + T_{20}$

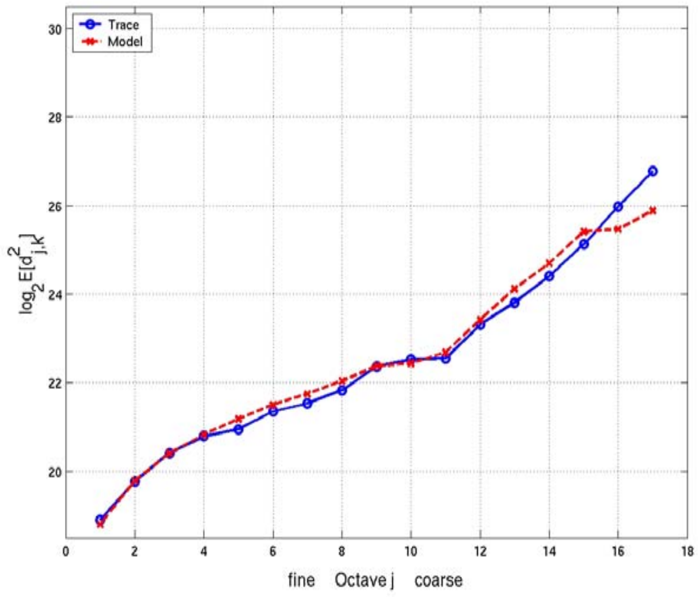
Model Parameters

T_{10}: Exp($1/\lambda_{10}$)
T_{11}: Pareto(K_{11}, α_{11})
T_{20}: Exp($1/\lambda_{20}$)
T_{21}: Pareto(K_{21}, α_{21})
B: Data rate within active period
N: Number of connections

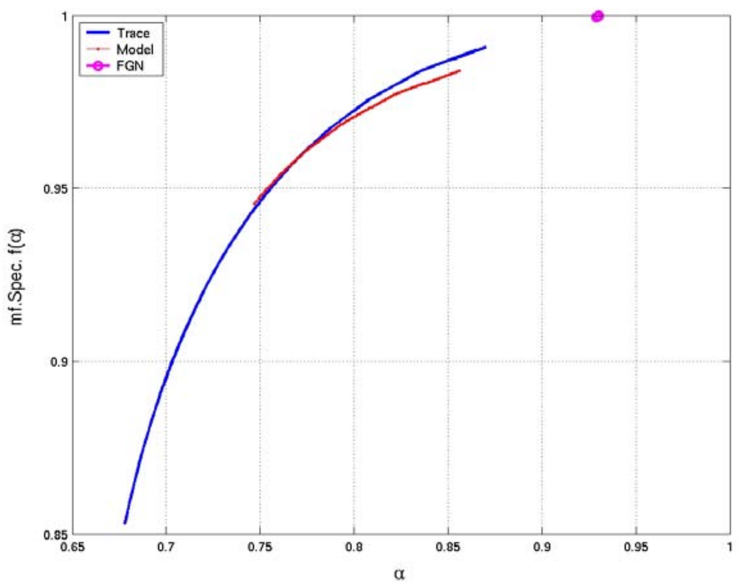


Synthesized Traffic of Model and Parameter Estimation

Developed, completed, tested and validated statistical parameter estimation from real traffic traces; simple and fast

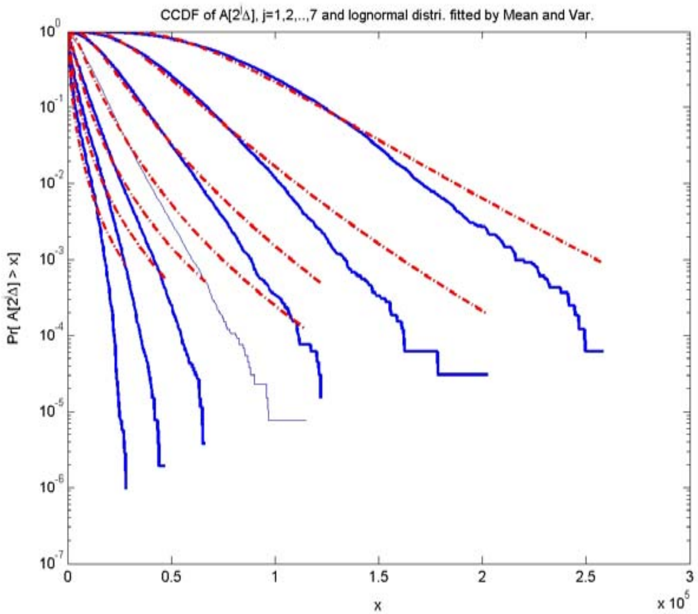


LogScale Diagram

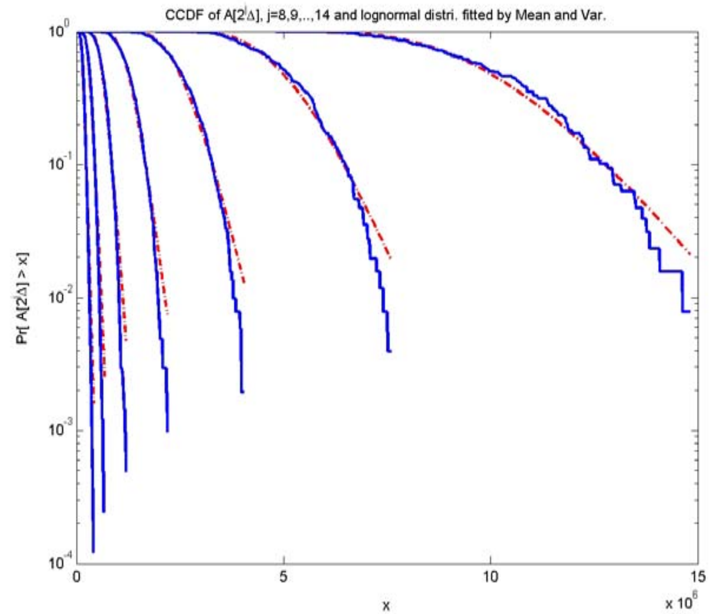


Multifractal spectrum

Lognormal Distribution of Workload fitted by Mean and Variance



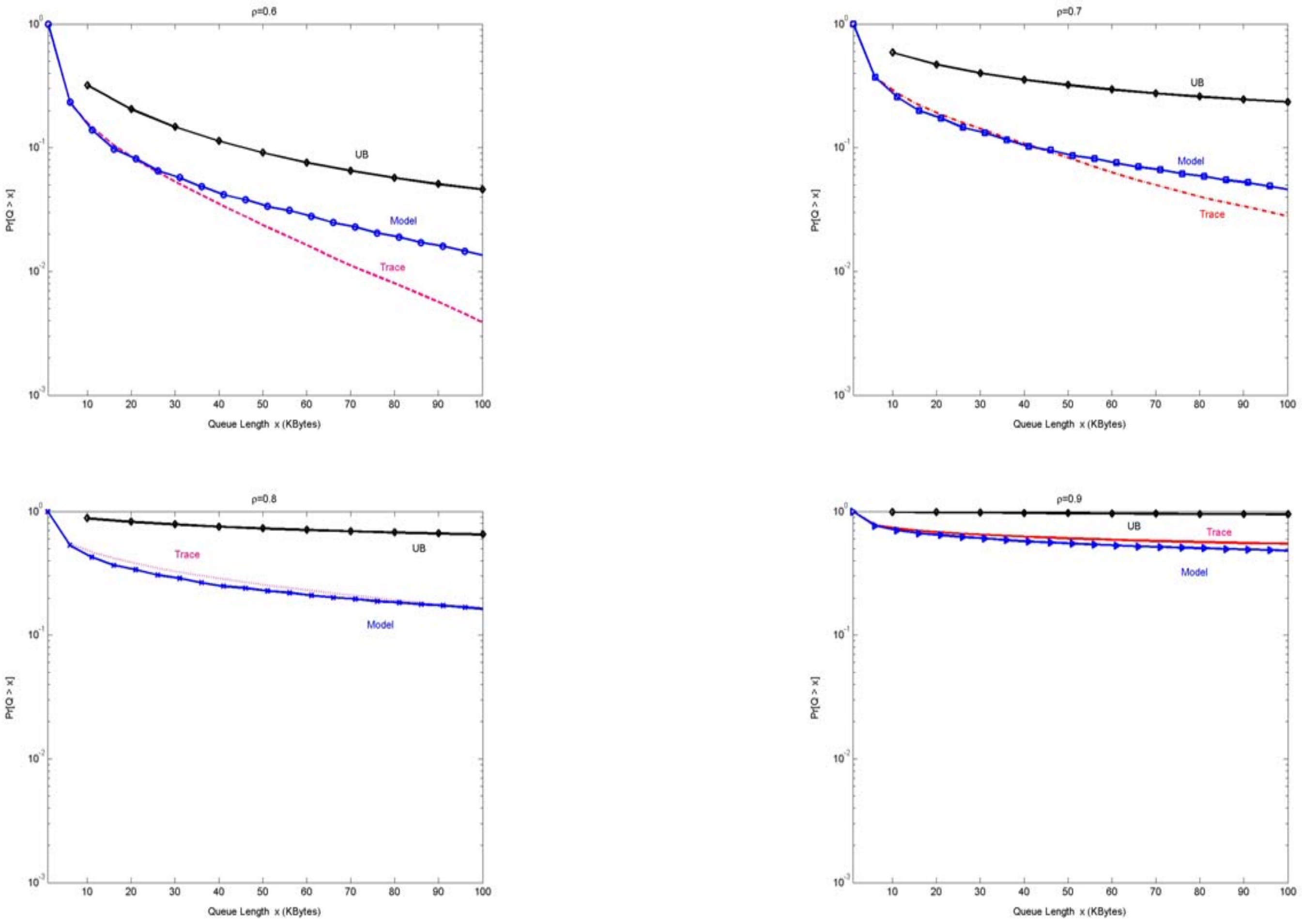
CCDF of workload
A[2 j*1ms], j=1,2,..,7



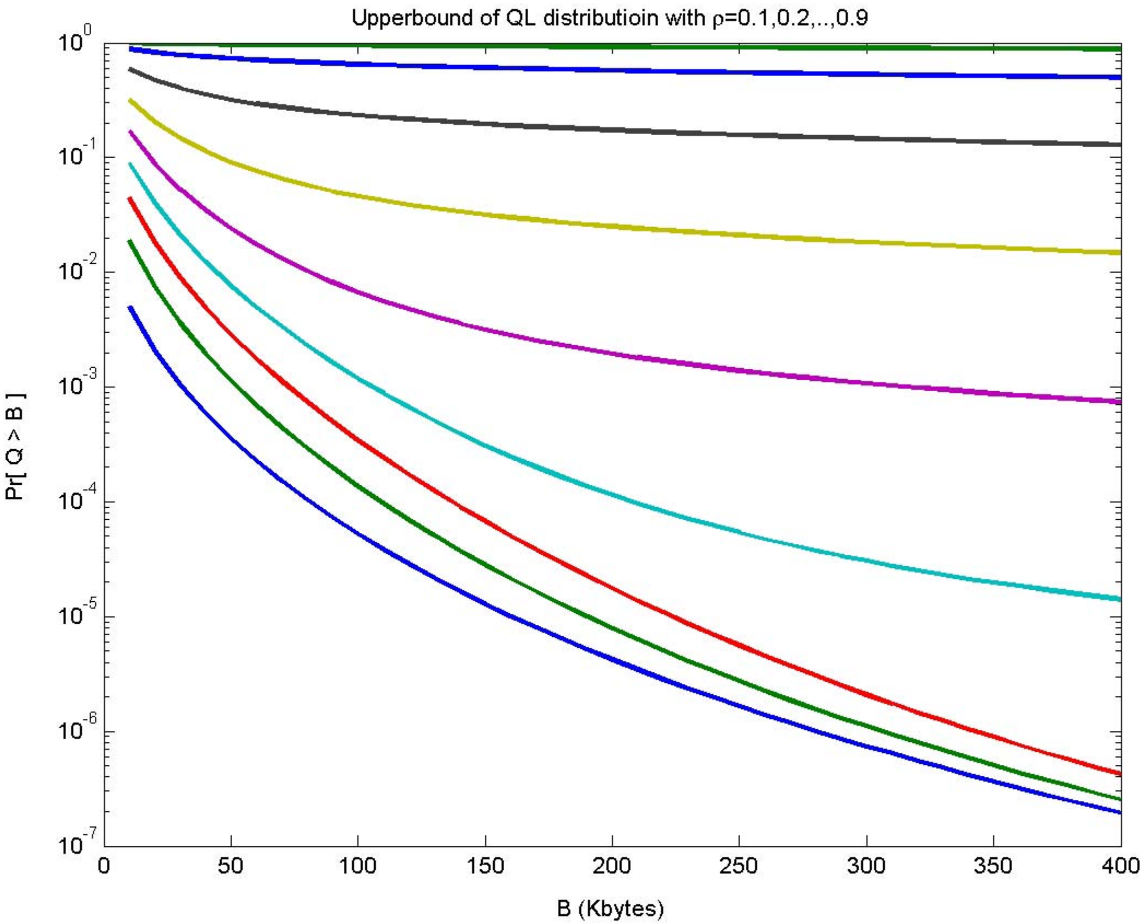
CCDF of workload
A[2 j*1ms], j=8,9,..,14

A[2 j] is the total bytes arrived in the interval [0, 2 j*Δ), (Δ is the smallest time interval).

Upper Bound of Queue Length Distribution



Upper Bound of Queue Length Distribution (cont.)



- Demonstrate which time scale is most important for queuing analysis as function of utilization and buffer size
- Also for queuing control

Active Queuing Management in Self-similar Traffic

(J.S. Baras, H. Chen, C. Zhang)

Objectives

- **Establish stochastic models for TCP traffic in the presence of AIMD end-to-end control and gateway control (RED) (non-Poisson traffic)**
- **Explore the performance of RED in terms of TCP congestion window and congestion node queue distribution. Generalized TCP window-based adjustment scheme and optimal ECN marking strategy. Robust Control.**
- **Propose unified view of congestion node and end node optimization as Markov decision processes (MDP) when treating non-Poisson nature of TCP traffic as MMPP (Markov modulated Poisson process)**

TCP Model

- **TCP end-to-end control is assumed to be additive-increase and multiplicative-decrease. Fluid model is used.**

$$\frac{d\lambda}{dt} = \underbrace{\frac{\lambda(t-R)}{\lambda(t)}\frac{1-p(t-R/2)}{R^2}}_{\text{Additive Increase}} - \underbrace{\frac{1}{2}p(t-\frac{R}{2})\lambda(t-R)\lambda(t)}_{\text{Multiplicative Decrease}}$$

- **λ is the TCP sending rate, R is the round-trip time, and p is the dropping probability at the gateway. Choice of p depends on different flavor of Active Queuing Management.**

Truncated Power-Tail Distribution

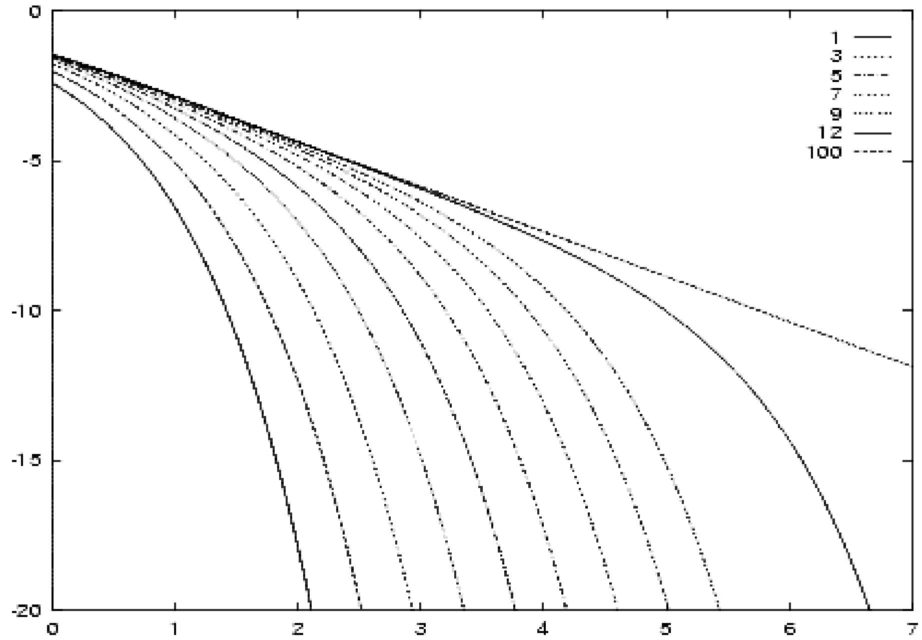
- **Use truncated power-tail distribution to emulate Pareto-distributed file size**

$$R(x) = \exp(-xB)\varepsilon',$$

$$p = \frac{1-\theta}{1-\theta^T}\left[1, \quad \theta, \quad \cdots, \quad \theta^{T-1}\right],$$

$$B = \mu \mathrm{diag}\left(1, \quad \gamma, \quad \cdots, \quad \gamma^{\mathrm{T-1}}\right),$$

$$0 < \theta < 1, \ \gamma = \left(\frac{1}{\theta}\right)^{1/\alpha}$$



Truncated-power-tail distribution

with $\alpha = 1.5$ **and** $\theta = 0.5$ **with**

$T = \{1, 2, \cdots, 9, 12, 100\}$

MDP Formulation

- **Discretize the TCP model; q is queue length, r is sending rate which is controlled by truncated power-tail matrix state x, and control policy u**

$$q_{k+1} = \max\{(q_k + \sum_{i=1}^{M} r_{i,k} - \mu), 0\}$$

$$z_{i,k+1} = r_{i,k} - u_{i,k} r_{i,k} / 2 + (1 - u_{i,k}) / d_i^2, \quad i = 1, \cdots, M$$

$$p(r_{i,k+1} = z_{i,k+1}, x_{k+1} = m \mid r_{i,k}, x_k = n) = P_{n,m} \delta(r_{i,k+1} = z_{i,k+1})$$

$$p(r_{i,k+1} = 0, x_{k+1} = 0 \mid r_{i,k}, x_k = n) = P_{n,0}$$

- **Value function can be defined on weighted sum of queuing delay, gateway throughput, drop rate and fairness index**

Dynamic Programming Approach

- The state variable $i=\{q,r_1,r_2,\ldots,r_M,x_1,\ldots,x_M\}$, where M is the number of sources and q is the queue length.
- Immediate transition costs:

$$g_k = w_1 Q_k + w_2 D_k + w_3 F_k - w_4 T_k$$

where

- $T_k=min(q_k,\mu)^2$
- $Q_k=q_k^2$
- $Dk=\sum_i u_{i,k}^2$
- $Fk= \sum_{i\neq j}(r_{i,k}-r_{j,k})^2$
- w_1, w_2, w_3 and w_4 are weights.

- Objectives:
  - Average-cost $\lim_{K\to\infty} \min E\{\frac{1}{K}\sum_{k=0}^{K} g_k\}$
  - Discounted-cost $\lim_{K\to\infty} \min E\{\sum_{k=0}^{K} \beta^k g_k\}$

Approximation Schemes:

- DCA (Direct Computation based on state Aggregation)
- DHDP (Distributed Hierarchical Dynamic Programming)

TCP Model for Wireless Links

(J.S. Baras, G. Papageorgiou)

- Multiple flows sharing the bottleneck wireless link
- Need for a realistic packet loss model exhibiting strong correlation between packet losses
- Address issues of fairness and flow synchronization
  - Would provide insight for a better MAC design

Hybrid TCP Model

- Captures both the "higher-level" discrete model and the "lower-level" continuous-time mode of operation
- Results for the transient as well as the steady-state behavior of the TCP
- Provides formal proof of multiple TCP flow synchronization
- It needs extension to take into account non-deterministic events like random packet losses over a wireless link

Another Simple TCP Model

- All analytical TCP models proposed fail to capture the Slow-Start phase of TCP, which is strongly associated with Timeouts
- Timeouts in TCP flows that pass through a wireless link are expected to be frequent events, so Slow-Start should be considered in a realistic model of TCP
- Taking into account the whole congestion control mechanism of TCP as described in RFC 2001/RFC 2581, the probabilities describing the window size evolution can be derived

Another Simple TCP Model

- For the Slow-Start phase:

$$
\begin{aligned}
&Pr\{W_{n+1} = W_n + 1\} = \\
&\qquad Pr\{W_n < sshthresh\} - \\
&\qquad Pr\{DUP|W_n < ssthresh\}Pr\{W_n < sshthresh\} - \\
&\qquad Pr\{TO|W_n < ssthresh\}Pr\{W_n < sshthresh\}
\end{aligned}
$$

- For the Congestion-Avoidance phase:

$$
\begin{aligned}
&Pr\{W_{n+1} = W_n + \frac{1}{W_n}\} = \\
&\qquad (1 - Pr\{W_n < sshthresh\}) - \\
&\qquad (Pr\{DUP\} - Pr\{DUP|W_n < ssthresh\}Pr\{W_n < sshthresh\}) - \\
&\qquad (Pr\{TO\} - Pr\{TO|W_n < ssthresh\}Pr\{W_n < sshthresh\})
\end{aligned}
$$

- For the case of a Timeout: $Pr\{W_{n+1} = 1\} = Pr\{TO\}$
- For the case of Dup ACK: $Pr\{W_{n+1} = ssthresh\} = Pr\{DUP\}$

Another Simple TCP Model

- To compute these probabilities the packet loss process should be known
  - This process describes the correlations between the packet losses and is an input for this simple TCP model
- Next step: introduce mobility
  - Mobility introduces a more complicated packet loss scheme, which can be described also through the packet loss process
- Solutions specific to the transport layer can be developed to deal with the problems introduced by mobility, e.g. movement prediction in cellular networks
- The performance of TCP in ad-hoc networks can be investigated with respect to specific movement patterns, e.g. clustering

Congestion Control: Modeling Difficulties

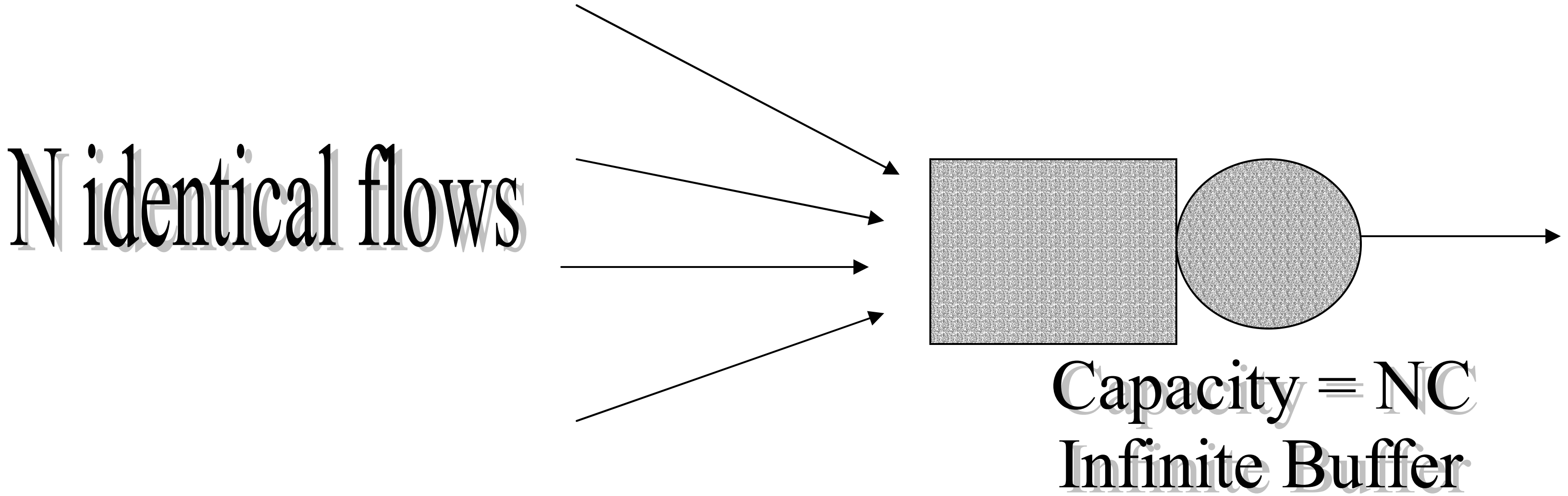
(A. Makowski, P. Tinnakornsrisuphap and S. Vanichpun)

- Interaction of congestion control and RED is poorly understood due to non-linearities and random delays
- Existing models are
  - too simplistic
  - too crude (e.g., ad-hoc approximations)
    - Enforced average to reduce number of states
    - Fixed point approximations

$$\frac{d\overline{w}}{dt} = \frac{dw_i}{dt} \qquad E[f(X)] \approx f(E[X])$$

A Simple Model

- Discrete time with slotted time
- Recursive queue dynamics – similar to Lindley's recursion.



Basic Ingredients

- N flows multiplexed at a RED gateway
  - Infinite capacity buffer
  - Scaled release rate of NC packets/slot
  - Rejection probability function based on scaled queue size Q_N(t)/N
- AIMD + RED model
  - Rate-based model
- TCP+ ECN/RED model
  - Window-based model

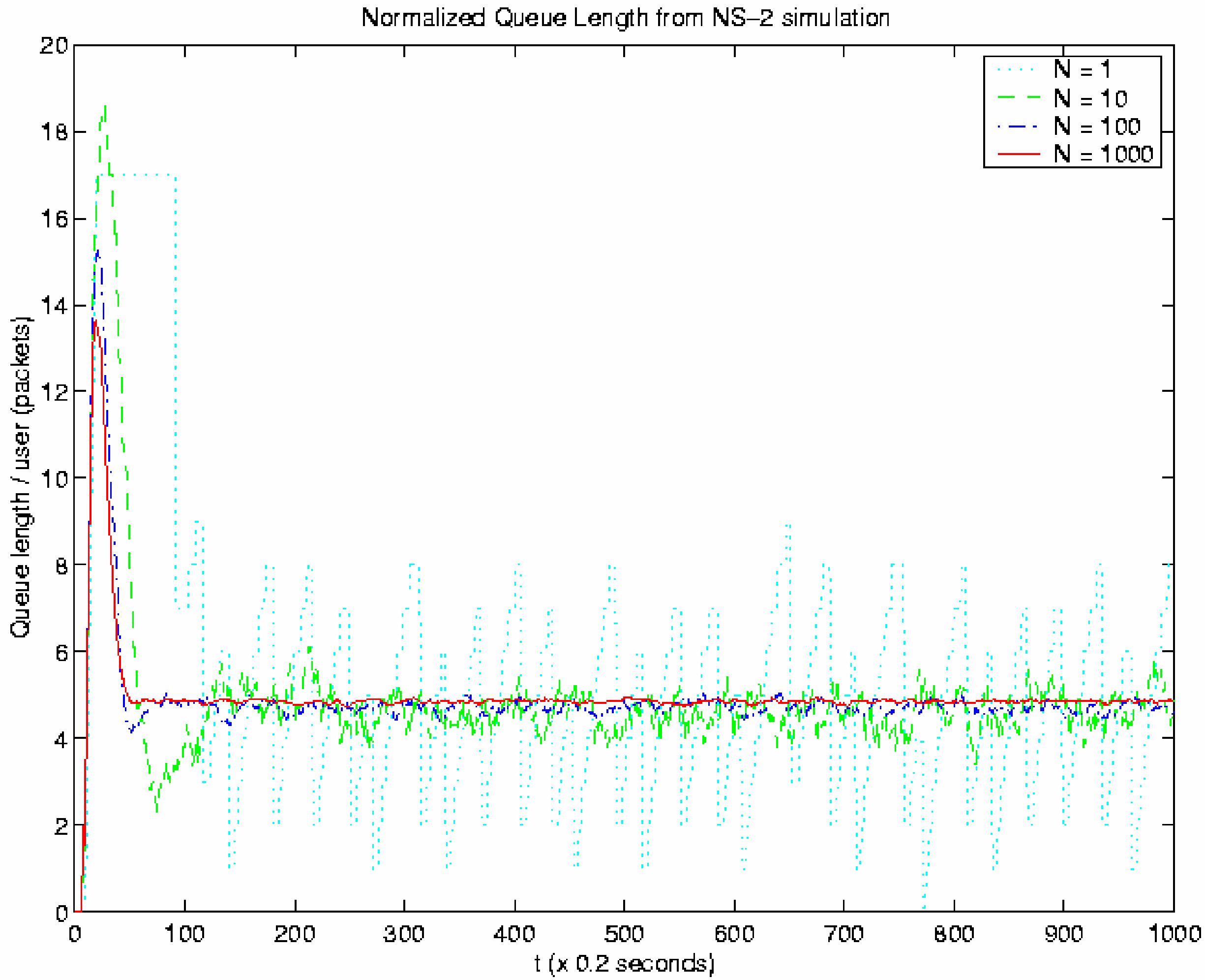
With N large, …

- Model simplification occurs – Key features include
  - Q_N(t)/N obeys a LLNs
  - Asymptotic independence among flows
  - Two-dimensional recursion
- Aggregate behavior is easier to track and estimate, with rough network dimensioning possible by approximating the RED buffer levels
  - Q_N(t) = N Limit (t) + …
  - Correction terms obey CLT

Benefits

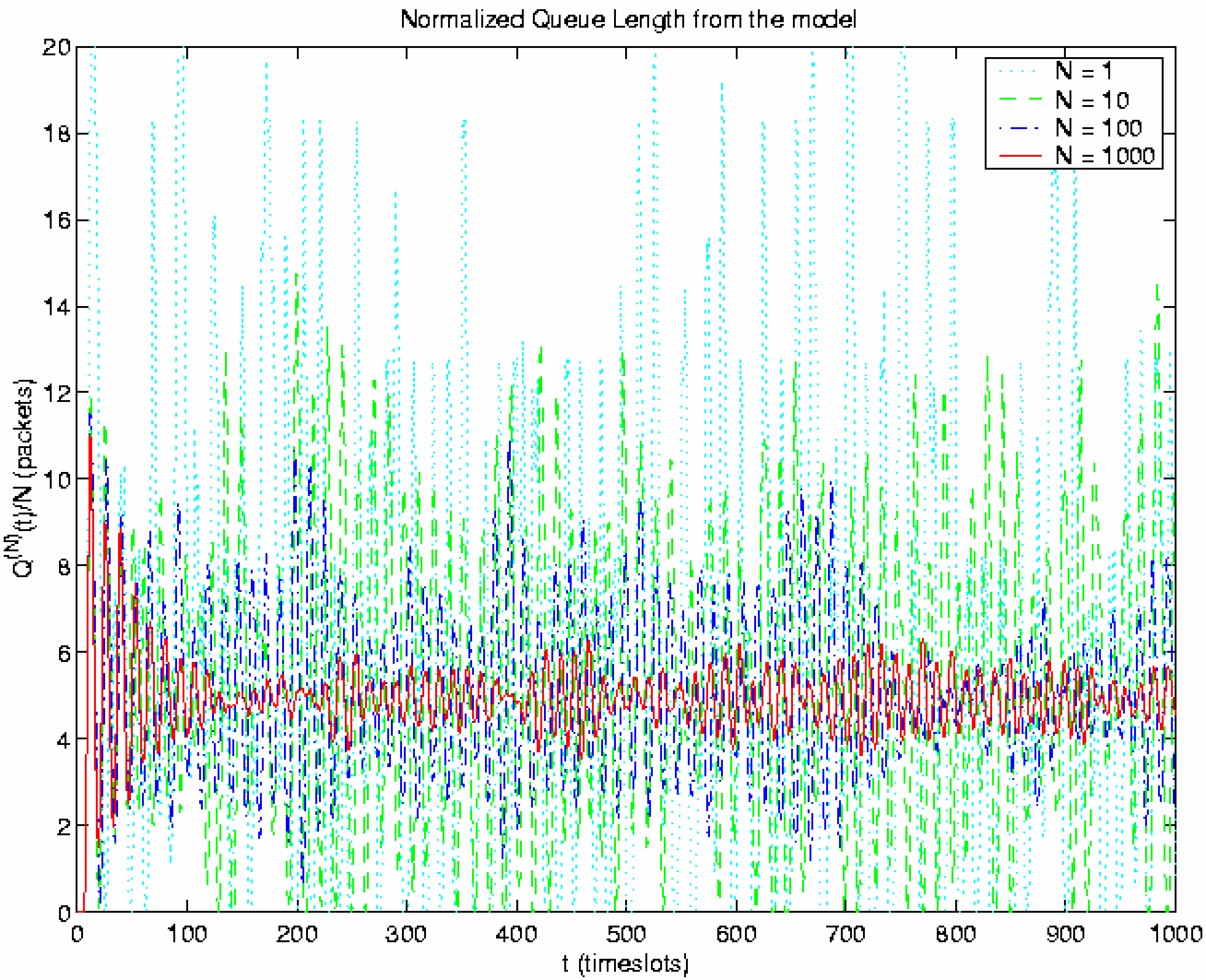
- As theoretical results compatible with NS-2 simulations in both models, argument for macro-modeling
  - Simpler load characterizations
  - Compact simulation models
- Impact of rejection probability function is made more apparent via the limiting model
- Mathematically rigorous with no ad-hoc approximations

Simulation Results



Queue length per user from the NS Simulation.

Simulation Results



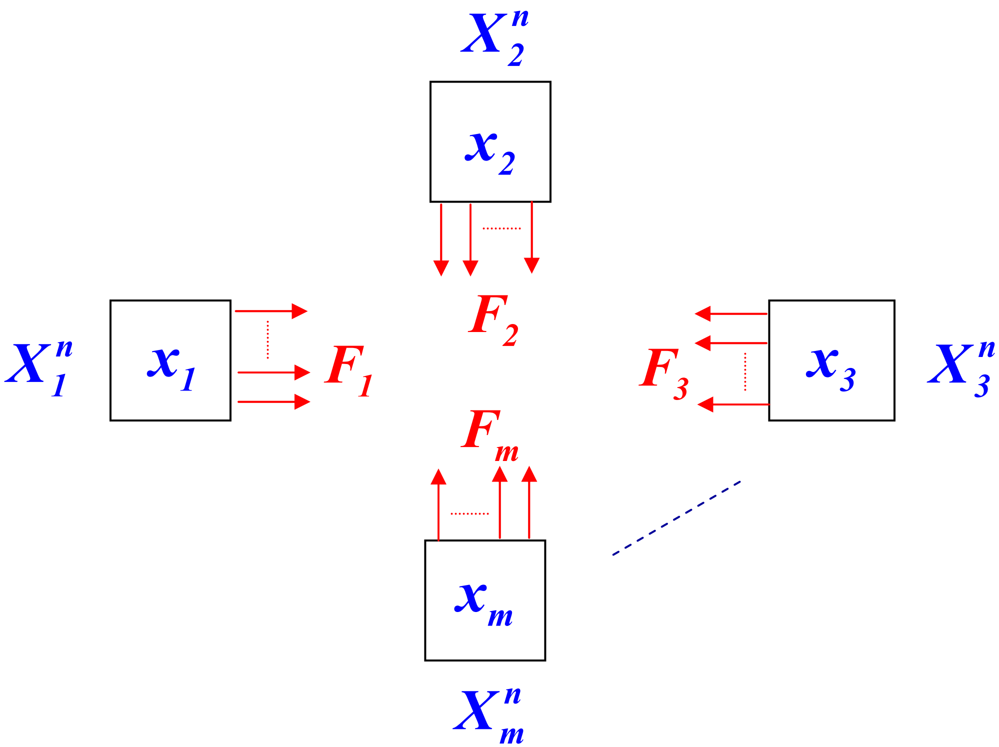
Queue length per user from the Monte Carlo Simulation of the window-based model

Secret Key Generation in a Network: An Information Theoretic Approach

(P. Narayan, C. Ye)

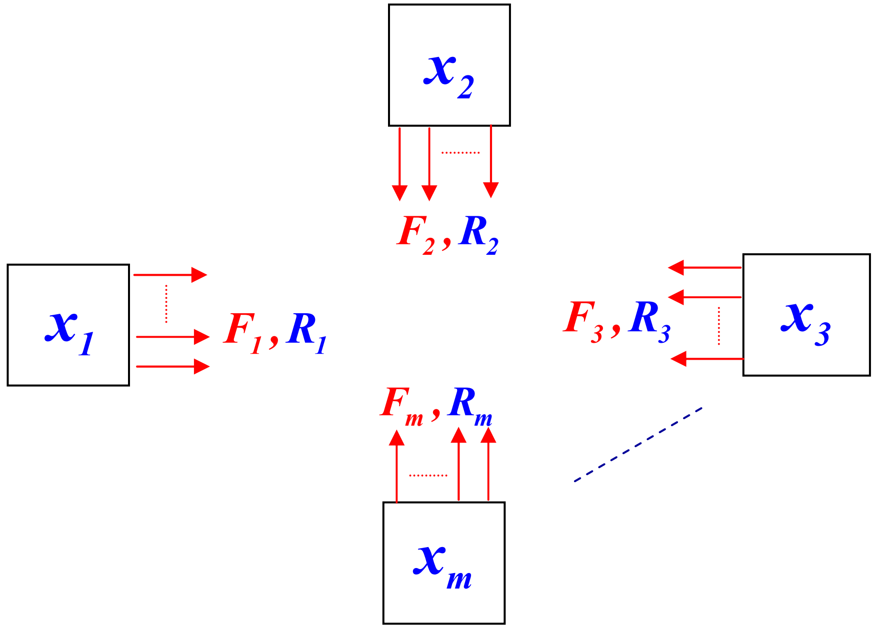
- Based on the notion of information theoretic secrecy.
  - Guarantees that legitimate messages and secret keys are "statistically independent" of eavesdropper's information.
  - No limitations are assumed on eavesdropper's computational resources.
- Complements the current approach based on the notion of computational security.
  - Security of existing cryptosystems is based on *current* "hardness" of underlying computational problem, e.g., factorizing into primes or computing discrete logs.
  - Implicitly assumes that computational power of eavesdropper is restricted.
  - Recent advances in quantum computing and prime-factorization raise concerns about extent of computational difficulty.
- Desirable to design cryptosystems which are *provably secure* without any restrictions on eavesdropper's computational power.

The Model



- The terminals are allowed to communicate over a *noiseless public* channel, possibly interactively in several rounds
- All transmissions are observed by all the terminals as well as by the eavesdropper

The Model



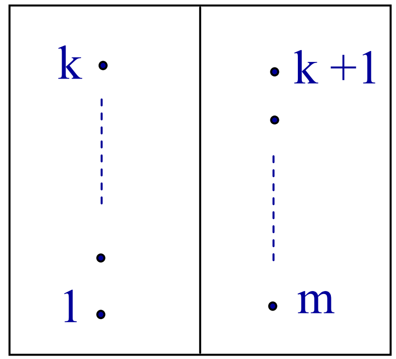
- Rate constraints on communication: $\dfrac{1}{n} \log \|F_i\| \leq R_i, \; i = 1, \ldots, m.$

Overview

- We consider models with an arbitrary number of terminals
- Each terminal observes a distinct component of a discrete memoryless multiple source
- Rate-constrained public communication (broadcast) is allowed between these terminals
- An eavesdropper observes the communication between the terminals, but does not have access to any other information

Secret Key Capacity

A^c : "helper" terminals



A : "user" terminals

Secret Key: *A function K of $(X_1^n, \ldots, X_m^n)$ is a SK for a set of terminals $A \subseteq \{1, \ldots, m\}$, achievable with communication $F_1, F_2, \ldots, F_m$, if*

$$K = K_{k+1}(X_{k+1}^n; F_1, \ldots, F_m) = \cdots = K_m(X_m^n; F_1, \ldots, F_m) \text{ w. p.} \cong 1 \quad (\text{"common key"})$$

$$\frac{1}{n} I(K \wedge F_1, \ldots, F_m) \cong 0 \qquad (\text{"secrecy"})$$

$$\frac{1}{n} H(K) \cong \frac{1}{n} \log |\mathcal{K}| \qquad (\text{"uniformity"}),$$

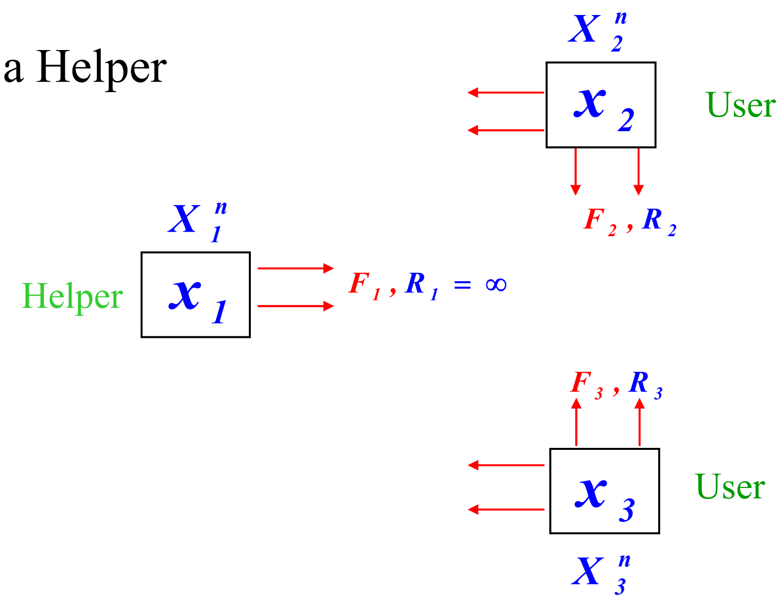
where $\mathcal{K}$= set of all possible values of K.

SK Capacity: *$C_{SK}(A)$ = largest achievable SK-rate for A.*

Thus, a secret key is effectively concealed from an eavesdropper with access to $F_1, \ldots, F_m$, and is nearly uniformly distributed.

Preliminary Result

Special Case: Two Users and a Helper



- $m = 3, A = \{2, 3\}.$

- $C_{SK}(A) = \max\limits_{U,V}[I(U \wedge XZ) + I(V \wedge XY|U)] - \max\{H(X|Y), H(X|Z)\},$

  where U and V satisfy

$$U - \circ - XY - \circ - Z$$
$$V - \circ - XZU - \circ - Y$$
$$I(U \wedge XY) - I(U \wedge XZ) \leq R_2$$
$$I(V \wedge XZ|U) - I(V \wedge XY|U) \leq R_3.$$

Work in Progress

- Application of Slepian-Wolf data compression techniques to secret key generation
- Models with rate constraints imposed on the public communication
- Models with wiretappers

Simulation-based Comparison of Routing Algorithms in Wireless Ad-hoc Network

Introduction

- **Objectives**
  - Implement a NS-2 based simulation of mobile ad-hoc networks with the following routing algorithms: TORA, AODV, OLSR, DSR, other
  - Evaluate differences between each routing algorithm to demonstrate the use of simulations for network management
- **Simulation Platform**
  - NS-2 simulator with CMU wireless extension
- **Scenario**
  - 50 mobile nodes, each moving randomly with constant velocity < 20 meters per second for a random duration then stop, and change direction within the simulated area of 1500x500 meters. 20 nodes are always actively involved in the generation of traffic (voice, data or video clips as specified in the traffic model slides). Varying the number of nodes involved in traffic generation is one way to scale network traffic without changing traffic model parameters.

Simulation Modules

- **Physical Layer / Path Loss**
  - Omni-directional antenna. Received power is calculated by Friis free space equation. Capture threshold = 10 dB, i.e., the power difference between the receiving packet and other interfering packets needs to be greater than 10 dB for this packet to be captured successfully.
- **MAC Layer**
  - IEEE 802.11 with transmission power = 0.28 watt corresponds to 250 meters transmission range, link data rate 11 Mbps
- **Routing Protocols**
  - TORA / AODV / OLSR/ DSR
- **Transport/Network Layer**
  - UDP / IP
- **Application Traffic**
  - Source/destination pairs are randomly chosen from the set of active nodes.
  - Intermediate nodes route traffic as needed.
  - All nodes are randomly positioned throughout the simulated area and are subject to random movement as specified in the mobility module.

Simulation-based Comparison of Routing Algorithms in Wireless Ad-hoc Network

Simulation Modules

- **Mobility**
  - Random waypoint model randomly selects the destination for a node in the simulated area of 1500 x 500 meters. This node moves to the destination with constant velocity randomly selected between 0 and 20 meters per second. Both the destination coordinate and velocity are generated according to the uniform distribution. Once at the destination, the node pauses for 10 seconds before performing another movement to another waypoint.

Performance Metrics

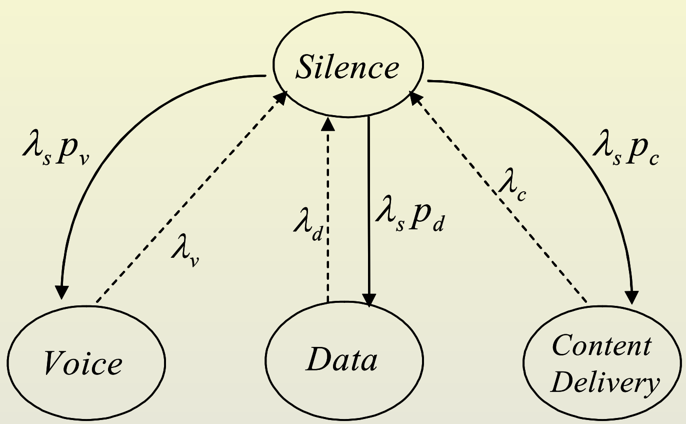
- Packet loss percentage per traffic class
- Average end-to-end delay per traffic class
- Overall goodput = total data packets received at the destination divided by the total packets received by all nodes
- Number of packets transmitted versus time in each traffic class

ADDITIONS: Link failure model, power schedules, directive antennas, dynamic bandwidth allocation

Simulation-based Comparison of Routing Algorithms in Wireless Ad-hoc Network

Traffic Models (user profile)

Every node in the network switches between four states according to a Markov process:



Sample Settings:

$\lambda_v = 3.33\times10^{-2}$ $\quad p_v = 0.944$

$\lambda_d = 8.33\times10^{-3}$ $\quad p_d = 0.037$

$\lambda_c = 7.50\times10^{-2}$ $\quad p_c = 0.019$

$\lambda_s = 2.02\times10^{-2}$

These settings will result in:

Stationary distribution of the chain(fraction of time at each state):

$P_s = 0.6$

$P_v = 0.344$

$P_d = 0.053$

$P_c = 0.003$

Also, the average waiting time at each state is:

$\tau_s = 49.5\sec s$

$\tau_v = 30\sec s$

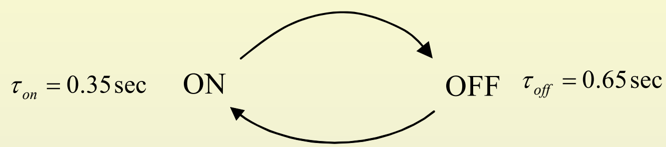
$\tau_d = 120\sec s$

$\tau_c = 13.33\sec s$

The network load also depends on the characteristics of the three services.

Traffic Models (application definitions)

Voice: ON/OFF process with exponential ON and OFF durations.



Constant rate of 8kbps during the ON period.

Data: ON/OFF process with ON and OFF durations having a Pareto distribution with shape factor 1.5.
Average ON duration = 8secs Average OFF duration = 20secs
Constant rate of 64kbps during the ON period.

Content-delivery (video clip): constant bit rate flow with high rate(300kbps). Session durations are exponentially distributed with mean 13.33secs.

The above settings result in equal share in the total amount of traffic generated by the voice, data and content-delivery services.